INVESTIGATIONS OF STEEL ELEMENTS WITH INTUMESCENT COATING CONNECTED TO SPACE-ENCLOSING ELEMENTS IN FIRE

Fire tests on intumescent coated steel members

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Abstract

The current status of the research program "Optimized use of intumescent coating systems on steel members" (AiF 17200) is presented.The aim of the project is to quantify the influence of space-enclosing elements on the thermal behaviour of supporting steel members. Those elements cause partially restrained expansion of the fire protection system. Experimental investigations on beams and columns directly connected to space-enclosing elements are presented. Additionally, numerical simulations are performed for temperature field calculations of steel elements with intumescent coating. As a new development, the numerical model takes into account the expansion process of intumescent painting. The setup of the numerical model is introduced.

Keywords: intumescent coating, numerical simulation, fire tests

INTRODUCTION

The fire resistance of steel members protected by intumescent coating (IC) depends strongly on the expansion behavior of the fire protection system. In practical application, structural steel elements are often connected to space-enclosing elements like trapezoidal sheeting, liner traysand sandwich elements. Consequently, parts of the cross-sections are covered by adjacent space-enclosing elements (compare Fig. 1 and 2). In these regions the intumescent coating system is restrained in its expansion and is not able to develop an effective fire protection for the steel elements. As a consequence, the cross-section will be heated up not only in response to the behavior of the intumescent char but alsodepending on the isolation and the additional heat transfer provided by adjacent elements.This may lead to a non-uniform temperature distribution in the cross-section.

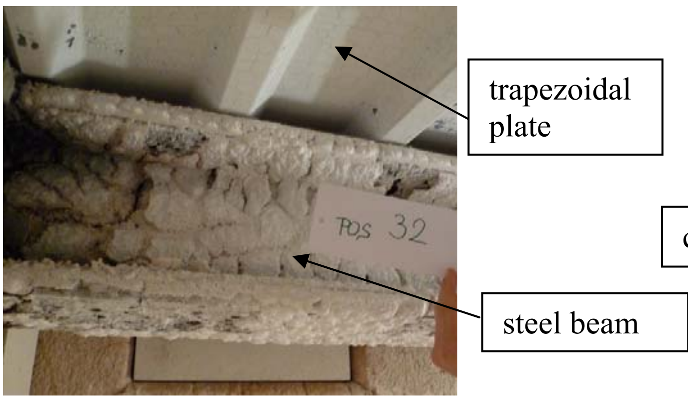


Fig. 1 Loaded Beam with IC and trapezoidal plate after test

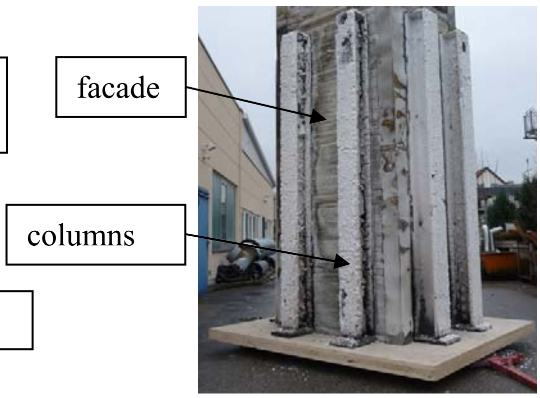


Fig. 2 Columnswith IC and connected façade after test

Usually, a uniform temperature distribution is assumed in structural fire design of steel elements. This simplification enables comparably simple calculation methods for the heating of steel sections in case of fire. SuiTab. formulae are given in [DIN EN 1993-1-2] for instance. However, for steel elements protected by IC and locatedadjacent to space-enclosing elements it is not clear, if this assumption is valid due to a possible non-uniform temperature distribution caused by the aforementioned effects.
The main research approach aims to investigate, if the covered parts of the steel elements (e.g. the flanges) need to be protected by ICor may be left unprotected. Therefore, full scale fire tests of steel beams and columns with adjacent trapezoidal plates have been performed. The test setup and first results are presented in this paper. Additionally, these investigations are supported by numerical analyses. In these analyses the temperature field of steel elements with IC is calculated taking into account the expansion process of IC. Furthermore, shrinkage procedures due to combustion of the organic parts of IC are considered as well. The numerical model and the material parameter for IC used in the thermal calculations are presented in this paper.

1 TEST ARRANGEMENTS

In the experimental program two different setups were carried out:loaded beam tests and unloaded column tests. All tests were carried out over a period of 30 minutes ISO-Standard fire. The thickness of the intumescent coat on all test specimens has also been designed for 30 minutes fire resistance in regard to German regulations.

1.1 Loaded beam tests

The furnace used at the Fire Test Laboratory of the Technische Universität München is 3m wide 4m long and 3m high. For the tests on the loaded beams it was enlarged up to 5m length. In order to investigate the behaviour of beams in industrial halls 10 specimens HEA 200 and 10 specimens HEM 200 with a span of 4.5 m and two different types of trapezoidal sheeting were tested.
In order to achieve a constant bending moment over the length of more than 1m the beams were loaded with single loads in the third points of the span.
The load level chosen led to a bending moment in the beam sup to 60 % of the plastic bending capacity. The total load (applied with hydraulic cylinders) for HEA 200 beam sreached 80 kN, for HEM 200 beams220 kN.
Care was taken to realize a hinged support and an assembly typically used for industrial halls.

Fig. 3View from outside; the blue and grey columns and beams are the load admission

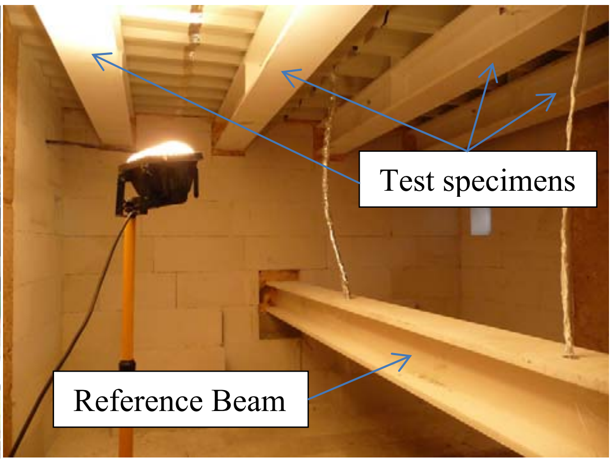


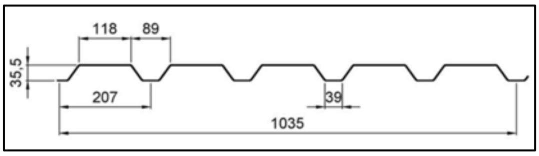
Fig. 4View into the furnace short before fire-test

120 thermocouples per test were used to obtain temperature gradients in the steel members and in the trapezoidal sheets. The trapezoidal sheets (thickness 0,88 mm) were fixed on the beams with Hilti powder actuated fasteners. The isolation material on the top of the sheets was 120 mm mineral wool (non-flammable, melting point higher than 1000°C) which is typical for industrial halls in Germany.

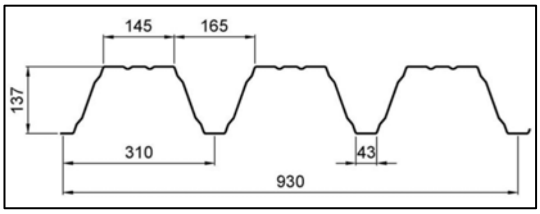
Tab. 1Number of test specimens (beams), in combination with the trapezoidal sheets.

BEAM	FischerTRAPEZ 35/207	FischerTRAPEZ 135/310	Without sheets (Reference)
HEA 200	**4**	**4**	**2**
HEM 200	**4**	**4**	**2**

"FischerTRAPEZ 35/207"



"FischerTRAPEZ 135/310"



1.2 Unloaded column tests

The column tests were also performed at the fire test site of TUM. A tower (columns with connected façade) was constructed which was slightly higher than the furnace (see Fig. 6-8)in order to simulate a typical situation at fires of industrial buildings where columns and the inner part of the façade sheets are exposed to the fire, but not the outer part of the façade. The measurement equipment was installed in the cool inner partof the tower.

Fig. 5 Column setup before the test

Fig. 6 Façade elements, which come through the furnace ceiling.In orderto prevent an overheating in the tower a ventilator,blowing air into the lower areaof the tower, guaranteed a continuous slow air draft from the tower floor to the ambient air

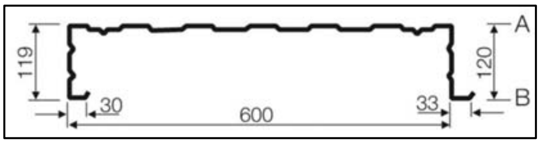
In total eight columns (four columns HEA 200 and four columns HEM 200) connected with two different types of industrial cladding were tested. For the first test a liner tray façade, filled with 120 mm mineral wool (non-flammable, melting point higher than 1000°C) and for the second test a standard sandwich panel consisting of two steel sheets (0,75 mm) and between 120 mm polyurethane foam was used.

Temperatures of the steel columns and the temperature of the directly flamed steel sheets were measured. The evaluation of the test results is on-going und will be published later.

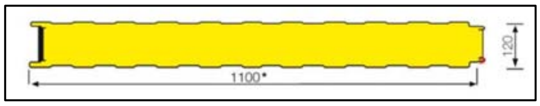
Tab. 2 - Number of test specimens (columns), in combination with the façade sheets.

COLUMN	FischerKASSETTE 120/600	FischerTHERM LL 120 NEU	Without sheets (Reference)
HEA 200	4	4	2
HEM 200	4	4	2

FischerKASSETTE 120/600



FischerTHERM LL 120 NEU



Pre-Evaluation of a beam
After 6 to 7 minthe intumescent coating starts to foam up.

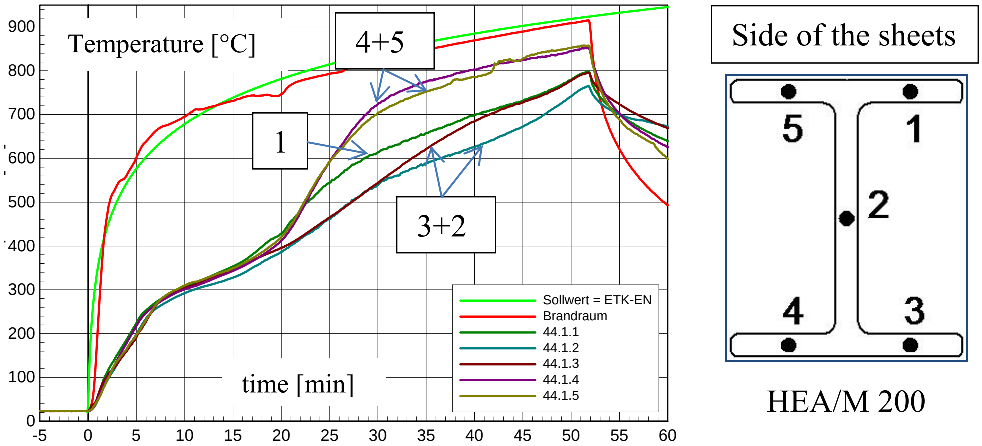


Fig. 7Example of a time-temperature course (test specimen 44)

Furthermore, an additional steel beam with intumescent coating has been tested under ISO fire conditions to investigate the thermal behaviour without any influences due to space-enclosing elements. Moreover, the numerical investigations will be validated against this test. In this test, an IPE 200 profile (S235) with a length of 1000 mm has been coated with a solvent based intumescent coating system and exposed to fire from all sides. The coating thickness amounted about 700 µm. The steel temperatures have been measured during the tests at different cross-section points. The evaluation of the steel temperatures in web and flange are depicted in Fig. 3.

2 NUMERICAL SIMULATIONS OF INTUMESCENT COATINGS

The performed fire tests indicate the importance of the expansion process of intumescent coating concerning the fire protection of steel elements. Regarding regions in which parts of the flanges are covered by space-enclosing elements, the intumescent coating is restrained in its expansion and is not able to develop effective fire protection behavior. Consequently, there are areas with fully developed char and areas in which the expansion of IC is restrained. As a result, it is absolutely necessary to take into account the expansion process in order to consider a restrained expansion process. In this context, a numerical model is introduced in which the expansion process is simulated explicitly.

In the numerical model which bases on the finite-element method (FEM), the expansion process of intumescent coating has been taking into account for thermal analysis. Influences of a restrained expansion process are not considered in the model yet. An implementation of these effects is in process. However, the numerical model represents a basis to take these special effects into account later. Besides the expansion process of intumescent coating, shrinkage as described in [Zhang et al, 2012] is considered as well.
The numerical simulations are performed using the finite-element software [ABAQUS] in a fully coupled 2D thermal-stress analysis. The expansion process has been implemented by defining a thermal expansion coefficient α according to the expansion behavior observed in the tests. The porosity can be calculated using the following expression:

$$\psi = 1 - \frac{1}{\alpha} \text{ [-]} \tag{1}$$

Based on this equation, the thermal conductivity can be calculated using an equation developed by [Spitzner, 2001] .

$$\lambda_{eq} = \frac{1}{1+\frac{1}{3}(1-\psi)} \cdot \lambda_{air} + \frac{2 \cdot \frac{1}{3}(1-\psi)}{1+\frac{1}{3}(1-\psi)} \cdot \lambda_{IC} + \frac{4 \cdot b}{1+\frac{1}{3}(1-\psi)} \cdot \varepsilon_{res} \cdot \sigma \cdot T_m^3 \quad \text{[W/(m·K)]} \tag{2}$$

with:

λ_{eq}	equivalent thermal conductivity	[W/(m·K)]
ψ	porosity	[-]
b	diameter of a pore	[m]
λ_{air}	thermal conductivity within of air the pores	[W/(m·K)]
λ_{IC}	thermal conductivity of IC (20°C)	[W/(m·K)]
ε_{res}	emissivity	[-]
σ	Stefan-Boltzmann-constant	$[W/(m^2 \cdot K^4)]$
T_m	average temperature of pores	[K]

For the determination of the thermal heat capacity of intumescent coating the *mixture-rule* is used:

$$C = (\rho \cdot c_p) = \psi \cdot (\rho \cdot c_p)_{air} + (1-\psi) \cdot (\rho \cdot c_p)_{IC} \quad \text{[J/(m³K)]} \tag{3}$$

The diameter of the pores is assumed as 0.5 mm according to [Staggs, 2010] and the thermal conductivity of IC for room temperature conditions is assumed to λ_{IC} = 0.5 W/(m·K). The specific heat of intumescent coating for room-temperature conditions is assumed as c_p = 1600 J/(kg·K) and the density as ρ = 1300 kg/m³. The expansion factor and the porosity versus temperature as well as the thermal conductivity and the heat capacity versus temperature are shown in Fig. 1.

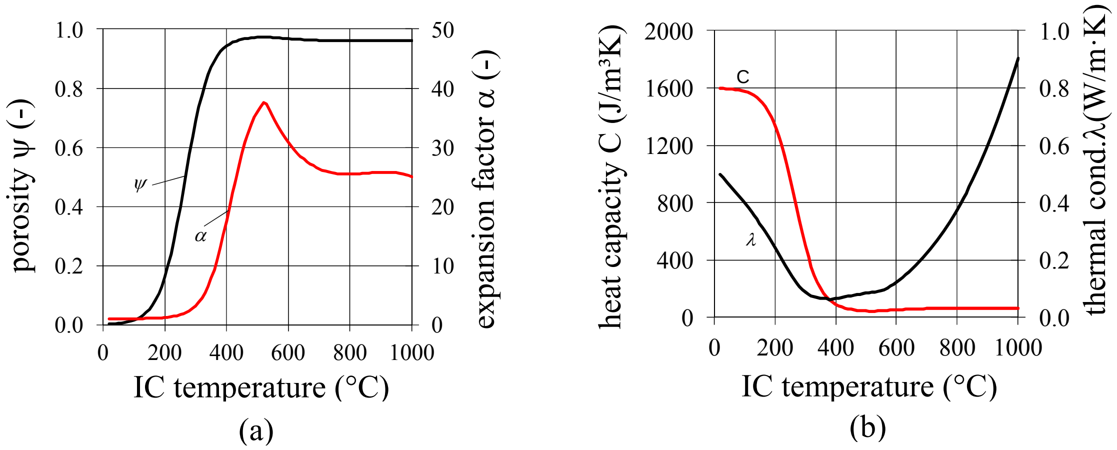


Fig. 8 – Evaluation of a) porosity and expansion and b) heat capacity and thermal conductivity versus intumescent coating temperature

In the thermal analysis the material behavior of steel, as well as the thermal boundary conditions for convection and radiation are set according to [DIN EN 1993-1-2].
Based on the aforementioned specifications, the expansion model will be applied to an I-section (IPE200) fire protected by intumescent coating without any influences from space-enclosing elements. In this context, the model will be validated against the experimental investigations described before.

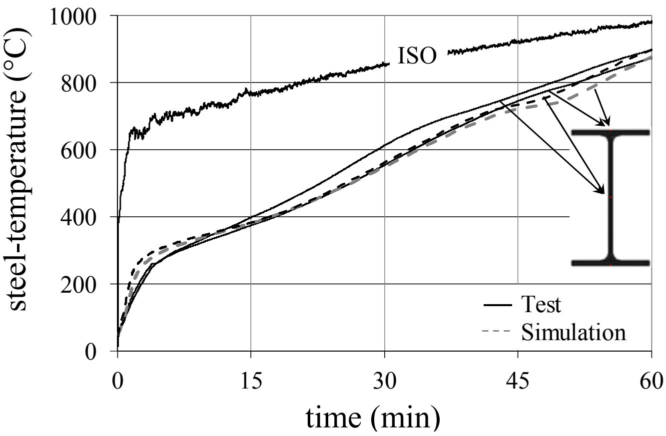


Fig. 9 – Comparison of simulated and measured steel temperatures of a IPE200 profile

Simulated and measured temperatures are compared in two cross-section points as indicated in Fig. 3. In particular the simulated temperatures in the flanges show very good agreement to the temperatures measured in the test. The temperatures in the web are slightly underestimated by the numerical simulation with a maximum deviation of about 25 C to the test. This small deviation is accepTab..
Summing up, the prognosticated temperatures are in good agreement with the measured ones and can be predicted by the model in good agreement.

3 CONCLUSIONS

In this paper, experimental investigations of steel elements with intumescent coating where parts of the cross-sections are covered by adjacent space-enclosing are presented. In additional numerical investigations, temperature field calculations of I-profiles with intumescent coating are performed taking into account the expansion process of intumescent coating. Furthermore, shrinkage procedures of the intumescent char are considered as well. Comparing the calculated steel temperatures to the measured temperatures form fire tests show good accordance. Consequently, the fire protection behavior of intumescent coating as well as the expansion process can be predicted. Based on the introduced model effects as a restrained expansion of intumescent coating due to space-enclosing elements will be implemented in further investigations.

4 OUTLOOK

The remaining work of the research project is focused on the evaluation and interpretation of the extensive test data. After these phase it will be possible to make correct declarations about the heating behaviour from steel members, connected with space-enclosing elements both experimentally and numerically.

5 ACKNOWLEDGEMENT

The authors would like to thank the sponsors of the project. Special thanks go to the German steel construction association DASt, the German ministry of economy and technology represented by the AiF, the construction company Goldbeck GmbH, that enabled with big

effort the assembly of the tests and the team of the fire test laboratory of the TechnischeUniversitätMünchenin Dachau. Further industrial partners of the project are: Sika Deutschland GmbH, Rüttgers Organics GmbH and Hilti Deutschland AG.
The results have been produced within the German research project:„Optimierter Einsatz intumeszierender Anstriche im Stahlbau“ (IGF 17200 N).The IGF project was funded by the “Federal Ministry ofEconomics and Technology” via AiF.

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Allgemeine bauaufsichtliche Zulassung Rütgers Organics GmbH Z-19.11-1889 Reaktives Brandschutzsystem „pyroplast-ST 200“

Allgemeine bauaufsichtliche Zulassung Sika Deutschland GmbH Z-19.11-1319 Reaktives Brandschutzsystem „Sika Unitherm LSA eco“